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Until recently scientists had limited opportunities to study human cognitive performance in non-laboratory, fully ambulatory situations. Recently, advances in technology have made it possible to extend behavioral assessment to the field environment. One of the first devices to measure human behavior in the field was the wrist-worn actigraph. This device , now widely employed, can acquire minute-by-minute information on an individuals level of motor activity. Actigraphs can, with reasonable accuracy, distinguish sleep from waking, the most critical and basic aspect of human behavior. However, rapid technologic advances have provided the opportunity to collect much more information from fully ambulatory humans. Our laboratory has developed a series of wrist-worn devices, which are not much larger than a watch, which can assess simple and choice reaction time, vigilance and memory. In addition, the devices can concurrently assess motor activity with much greater temporal resolution than the standard actigraph. Furthermore, they continuously monitor multiple environmental variables including temperature, humidity, sound and light. We have employed these monitors during training and simulated military operations to collect information that would typically be unavailable under such circumstances. In this paper we will describe various versions of the vigilance monitor and how each successive version extended the capabilities of the device. Samples of data from several studies are presented, included studies conducted in harsh field environments during simulated infantry assaults, a Marine Corps Officer training course and mechanized infantry (Stryker) operations. The monitors have been useful for documenting environmental conditions experienced by wearers, studying patterns of sleep and activity and examining the effects of nutritional manipulations on warfighter performance.

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Automated Ambulatory Assessment of Cognitive Performance, Environmental Conditions and Motor Activity during Military Operations

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ABSTRACT

Until recently scientists had limited opportunities to study human cognitive performance in non-laboratory, fully ambulatory situations. Recently, advances in technology have made it possible to extend behavioral assessment to the field environment. One of the first devices to measure human behavior in the field was the wrist-worn actigraph. This device, now widely employed, can acquire minute-by-minute information on an individual's level of motor activity. Actigraphs can, with reasonable accuracy, distinguish sleep from waking, the most critical and basic aspect of human behavior. However, rapid technologic advances have provided the opportunity to collect much more information from fully ambulatory humans. Our laboratory has developed a series of wrist-worn devices, which are not much larger then a watch, which can assess simple and choice reaction time, vigilance and memory. In addition, the devices can concurrently assess motor activity with much greater temporal resolution then the standard actigraph. Furthermore, they continuously monitor multiple environmental variables including temperature, humidity, sound and light. We have employed these monitors during training and simulated military operations to collect information that would typically be unavailable under such circumstances. In this paper we will describe various versions of the vigilance monitor and how each successive version extended the capabilities of the device. Samples of data from several studies are presented, included studies conducted in harsh field environments during simulated infantry assaults, a Marine Corps Officer training course and mechanized infantry (Stryker) operations. The monitors have been useful for documenting environmental conditions experienced by wearers, studying patterns of sleep and activity and examining the effects of nutritional manipulations on warfighter performance.

Keywords: vigilance, actigraph, sleep, ambulatory, Fourier, vibration, reaction time

1. INTRODUCTION

Novel technologies for assessing human behavior rarely emerge. Tests of cognitive performance and questionnaires, the most commonly employed behavioral assessment techniques, have been used since the emergence of psychology in the 19th century. While the technologies employed to conduct such testing have greatly improved, particularly since the advent of the mini- and microcomputer, the underlying parameters being assessed have not changed radically. For example, tests of reaction time, sensory capabilities and memory all emerged over 100 years ago and are still widely employed. One of the few completely novel technologies for the assessment of human behavior developed recently is the activity monitor, also know as the actigraph. This technology required the availability of microcircuits, specifically solid-state memory, but not microprocessors. Descriptions of several of the initial devices can be found in publications and patents dating from the 1970's and 80's.[1-3]

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Activity monitors continuously assess human motor activity and usually are worn on the wrist, leg or waist. The initial devices were relatively simple and consisted of little more than a piezoelectric crystal, minimal signal processing circuitry and very limited solid-state memory (less than 1,000 8-bit bytes).[1] Current devices now automatically record motor activity and other parameters over several days or weeks, in individual epochs lasting for periods of a second to several minutes. The most advanced have 8 megabytes of memory and internal microprocessors that are similar in computing power to Pentium processors. Actigraphs were developed, in part, to address the limitations of other technologies used to assess human behavior, especially the unsuitability of traditional methods for studying ambulatory human behavior. They provided an opportunity to study a new, previously unmeasurable aspect of human behavior, spontaneous motor activity, for long periods of time as individuals go about their daily activities.

2. PROBLEMS ASSOCIATED WITH AMBULATORY ASSESSMENT OF HUMAN COGNITIVE PERFORMANCE IN THE FIELD

Conventional tests of cognitive performance are administered using paper and pencil to fill out forms, computers to present stimuli and record responses, or with mechanical devices such as pegboards. These tests measure functions such as reaction time, vigilance, attention, learning, memory, manual dexterity and sensory function. Scientists rely on such tests to assess mental performance, but there are numerous problems associated with employing them, especially in the field. One limitation is that the volunteer must stop all ongoing activities to participate in testing. Another is that the equipment employed to administer them is often not portable. Cognitive tests can now be administered on notebook computers and Personal Digital Assistants (PDA), a significant advance in portability and convenience. Unfortunately, these devices have limited battery life, poor displays - particularly in outdoor conditions, inadequate keyboards and can be fragile. Using this instrumentation to study individuals in their natural environment can be intrusive and often impractical.

Activity monitors have some advantages over conventional technologies. They are typically much smaller then a personal computer or PDA, have a longer battery life, can be waterproofed and use of these devices to assess behavior does not require volunteers to interrupt their activities. They are particularly useful for measuring duration of waking versus sleep state, information that is extremely predictive of cognitive performance. Although lacking the accuracy and resolution of polysomnography (electrophysiological sleep assessment), the gold standard for assessment of sleep state, activity monitors have been widely and successfully used by investigators to assess sleep status in a wide variety of fields, ranging from academic psychology to clinical medicine[4]. They have also been used extensively to quantify human energy expenditure, although the accuracy of the devices for providing such information is not fully established.

3. THE EVOLUTION OF THE VIGILANCE MONITOR

Although actigraphs are valuable tools for assessing ambulatory behavior, they do not directly assess any aspect of cognitive function. Indirect inferences regarding the cognitive function of an individual wearing an actigraph are possible, since virtually all cognitive behaviors cease when an individual is sleeping. However, actigraphs provide no direct information regarding cognitive performance of humans. We have, therefore, modified the basic actigraph technology to enable direct assessment of certain aspects of cognitive performance. In effect, the unique aspects of the activity monitor were combined with a conventional technology for assessing cognitive performance by integrating the ability to present various stimuli and record responses with an actigraph. Because microelectronic and sensor technology has advanced rapidly since the development of the first actigraphs, a number of environmental sensors could be also be included in the new monitor. Sensors that could provide information on environmental factors known to be related to human behavior; specifically light, sound, and ambient temperature were incorporated into the device.

The first generation, integrated vigilance monitor, actigraph and environmental monitor that we designed was assembled in-house at our laboratory, the U.S. Army Research Institute of Environmental Medicine (USARIEM) (Fig. 1).[5-7] Since we lacked the facilities and resources to build a device from individual components, we used an off-the self datalogger engine as the motherboard for the device. The datalogger, a Tattle-Tale Model 5F, was designed for portable data logging applications and manufactured by Onset Computer Corporation, North Falmouth, MA. It contained an 8-bit microprocessor, RS-232 interface, analog-to-digital converter and 128 kilobytes of static random access memory flash memory. The microprocessor was a variant of the Motorola 6801, manufactured for Onset by a third party. This processor is roughly equivalent to the processor found in a first generation microcomputer, such as the Apple II. The Tattle-Tale device was designed by Onset to allow attachment of a daughterboard containing custom circuitry from third party developers. We designed such a daughterboard which contained a solid-state accelerometer, temperature sensor, light and sound sensor (microphone), as well as input and output devices including 3 LEDs, a miniature speaker, and two push buttons. To the best of our knowledge no such battery powered, portable device had ever been constructed previously.[5] The daughterboard was constructed so that all desired functions could be controlled by the microprocessor on the Tattle-Tale motherboard.

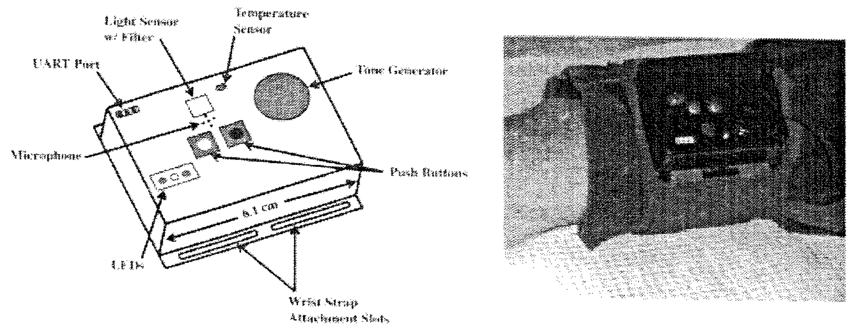

Fig. 1. Schematic and picture of the first version of the vigilance monitor.

The capability of using, in real time, the input from the sensors, presenting stimuli (auditory or visual) and recording responses from the wearer in any manner desired, under software control, provided a previously unavailable capability for studying and modifying human behavior and motor activity. As typically configured, the device recorded 7 channels of data (Fig. 2). The ability of the monitor to assess vigilance and reaction time is illustrated in Channel 4 of Fig. 2. Vigilance was assessed by presenting a random series of auditory stimuli and recording, by button-press, a response (or lack there of), and its latency with millisecond accuracy, to these tones. Since the device is fully programmable, it could potentially assess a wide variety of cognitive functions including learning, memory, pattern recognition, and reasoning.

As is often the case, once this new device was designed and produced, a wide variety of applications, some not envisioned when it was initially conceived, became possible. One potential application, which was obvious once it was clear that a device could be built to evaluate, in real time, responses of the wearer to stimuli, was to use the monitor to actively modify those responses. For example, when an individual does not respond to the stimuli presented, their intensity and frequency can be increased until a response occurs.[5-7] In the experiment shown in Fig. 2, to increase the likelihood a volunteer would respond, each individual stimulus presentation actually consisted of 3 consecutive tones, separated by several seconds, each somewhat louder then the previous tone. As soon as a volunteer responded to a tone in the series, presentation of the other tones was cancelled. This encouraged volunteers to respond rapidly, as they would then avoid subsequent tones in that series. In effect, the device can be programmed to increase the vigilance of the volunteer by measuring it directly in real time, and then providing feedback to the user when an unsatisfactory or no response is detected.

Since the device measures motor activity like an actigraph, data from this channel, such as low activity indicative of sleep, can be used alone or integrated with volunteer response data, to modify vigilance or patterns of sleep and activity. These capabilities could be employed to accomplish a variety of initially non-obvious objectives. For example, the device could be used, in theory, to modify an individual's circadian rhythms of sleep/activity and alertness by only permitting sleep during pre-programmed intervals. Another possible use would be to integrate the behavioral and environmental sensing capabilities so that in extreme environments an individual's motor activity, which is an indicator of work load, ambient temperature, and if desired, responsiveness to stimuli, were evaluated by an algorithm that would sound a warning if the individual appeared to be at risk. For example, high levels of activity in a hot environment could trigger an alarm to reduce the level of exertion of the wearer or, alternatively, test the wearer's behavioral responsiveness to external stimuli, and then act if it falls to unacceptable levels.[5]

Although the initial device fabricated in our laboratory was successfully used in a variety of studies, it lacked certain desirable features. One was the ability to present stimuli using the somatosensory modality, in particular to vibrate on command, like cellular telephones and pagers, which would permit behavior to be studied in noisy environments, or in individuals wearing helmets, where an auditory stimulus might be masked. Another advantage is the salience of such stimuli, since although it may be possible to ignore moderate volume auditory stimuli; a persistent somatosensory stimulus is difficult to disregard.[8] Other weaknesses of the first generation device were its relatively large size, limited memory by current standards and difficulty making it reliably waterproof (Fig. 1). Furthermore, because it employed a non-standard

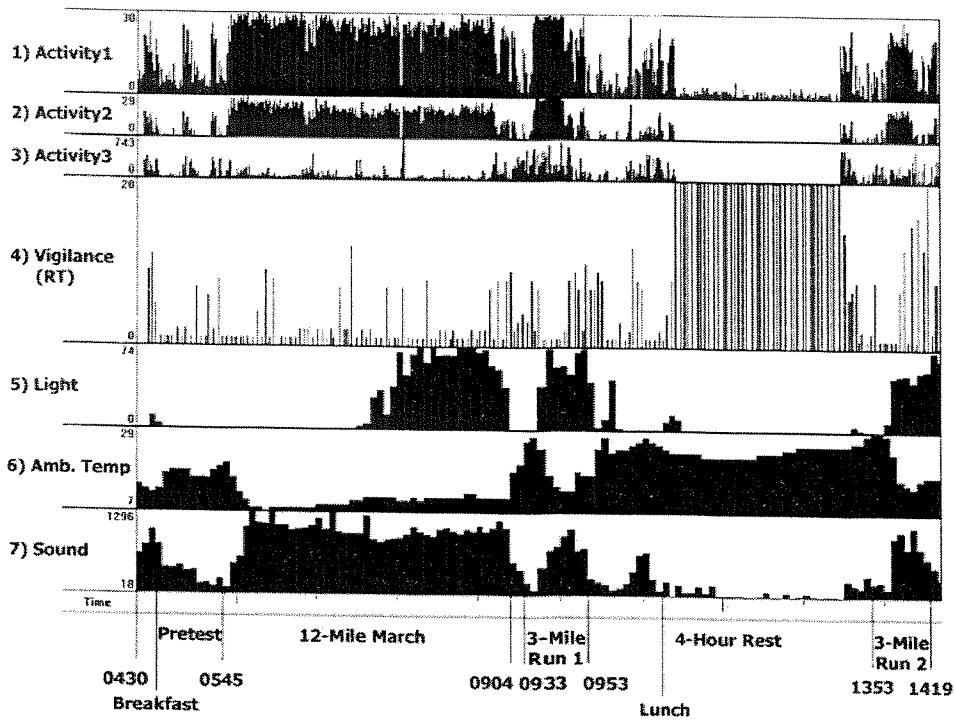

Fig. 2. Representative vigilance monitor data from one volunteer continuously collected over the 10 hours of a study designed to evaluate a carbohydrate beverage during a field exercise.[11] The seven channels of data that were acquired are labeled individually on the y-axis. Activities in which the volunteer was participating and clock hours are indicated on the lowest x-axis. CHANNEL 1-3: These three channels, Activity1-3, are sensing physical motion (acceleration) and data collected are similar to a standard actigraph. The vertical height of each line plotted on the x-axis represents the number of movements detected in one minute of time. Each channel is optimized to detect motion with different physical characteristics as described in the text. CHANNEL 4: This channel, labeled Vigilance (RT), displays the responses of the subject, in seconds, to the presentation of a sequence of tones (about 20/hour) at random intervals. The height of each bar represents the speed of response to the tone. When a bar reaches to the top of its graph this indicates that the subject did not respond to that stimulus. CHANNEL 5: This channel, labeled light, is the illumination level recorded at the wrist of the subject in arbitrary units. CHANNEL 6: The Amb. Temp channel continuously records ambient temperature in degrees Celsius. CHANNEL 7: This channel continuously records ambient sound levels in arbitrary units.

accelerometer, it could not be used to assess sleep using an existing, validated algorithm based on polysomnography.[9-10]

We collaborated with Precision Control Devices (PCD), Ft. Walton Beach, FL., to design a second generation vigilance monitor to eliminate these deficiencies (Fig. 3). The second generation vigilance monitor is waterproof, can generate vibratory stimuli and includes an additional environmental channel for recording humidity data. This capability was added since it is an important predictor of ability to work in hot environments. The second generation monitor uses the PIC 16F877 microprocessor, manufactured by Microchip Technology, Chandler, AZ., which is roughly equivalent to a 486-based microcomputer in processing capability.

This second generation device (Fig. 3) is smaller (5.6 cm x 4.3 cm x 1.6 cm) then the first generation vigilance monitor and initially contained 2 megabytes of non-volatile memory, so that in the event of a battery failure all data collected were retained. The devices were later modified to increase the onboard data memory to a total of 10 megabytes. This could be accomplished easily since the device was designed to permit upgrades when memory chips with larger storage capacities or new sensors became available. A major advantage of the second generation device is that it can sample activity to the identical specifications of PCD actigraphs. When activity is sampled in this manner, it can be used to

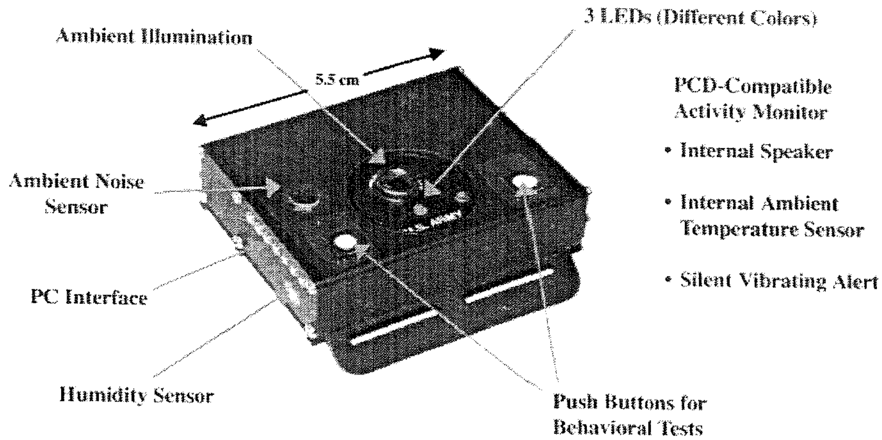

Fig. 3. Second version of the vigilance monitor with all sensors, output devices and push buttons identified.

distinguish sleep from waking, since algorithms to accomplish this have been validated using polysomnograpy.[9,10] Although the second generation device is smaller then the first generation device, some volunteers find it to be uncomfortable to wear for long periods of time (many days) and it is subject to physical damage when volunteers are in harsh environments. Since volunteers can, of course, take the devices off once they have left the laboratory, compliance with study requirements is encouraged by providing a more tolerable device.

Precision Control Devices has now produced a third generation monitor which is significantly smaller than the second generation device (Fig. 4). It is octagonal in shape, has 8 megabytes of memory and weighs only 48 g, yet preserves all the functions of the second generation device. Its dimensions are 3.8 cm x 3.8 cm x 1.2 cm, and its size and shape make it much more acceptable to the wearer since it is not much larger then a wristwatch (Fig. 4). In order to achieve software compatibility with the first PCD manufactured vigilance monitor, another Microchip Technology microprocessor in the same family was used in the device, the PIC 18LF6720. This microprocessor is approximately equivalent to a Pentium generation microprocessor. With 8 megabytes of data memory it could theoretically record 48 days of data in 9 channels every 10 seconds. Unfortunately, the battery would not last for that long.

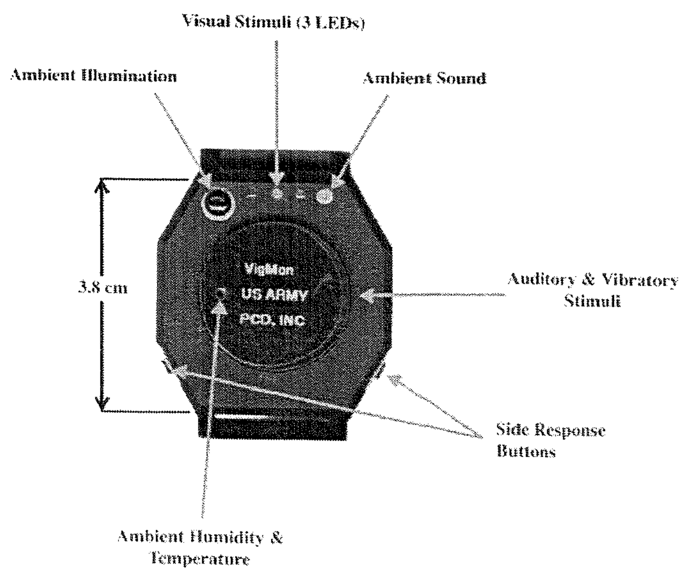

Fig. 4. Third version of the vigilance monitor with all sensors, output devices and push buttons identified.

4. MULTISPECTRAL ACTIGRAPHY

As noted above, one feature included in all generations of the vigilance monitor is activity assessment. The programmability of all versions of the vigilance monitor permits much greater flexibility in the recording and use of these data compared to standard actigraphs. For example, the first version of the vigilance monitor was typically programmed to sample and store three activity channels of data, each with different sampling characteristics, although it was not limited to this configuration. One channel was designed to be similar to a standard actigraph, one channel was less sensitive to low amplitude activity, but similar in its frequency response to the first channel, and a third channel was programmed to be sensitive to low frequency signals – slow movements or activities (Fig. 2).[6,7]

For one experiment, the device was programmed to be sensitive to frequencies in the 10 Hz range so it could, in theory, record cold-induced shivering. Standard actigraphs are not sensitive to frequencies in this range. Because of the relatively small amount of memory in the first generation device (128 kilobytes), and the higher sampling frequency required to assess shivering, the device could only record in this mode for several hours and could not record any other information. Activity in the 10 Hz frequency range assessed with the first generation vigilance monitor, and core body temperature simultaneously recorded by a rectal probe, are presented in Fig. 5. The young healthy male volunteers in this study were exposed to cold air (10° C) in a climatic chamber for up to 4 h. During the exposure they were sitting quietly on nylon webbed chairs so little physical activity was occurring.[14] As core body temperature decreased, it appears that high frequency activity increased and may have contributed to the stabilization of core temperature in the last hour of the exposure period, possibly as a result of shivering. Other actigraphs have also been used to sample high frequency activity for various purposes, such as detection of tremor in volunteers with Parkinson's disease or life signs in hospitalized patients.[12,13]

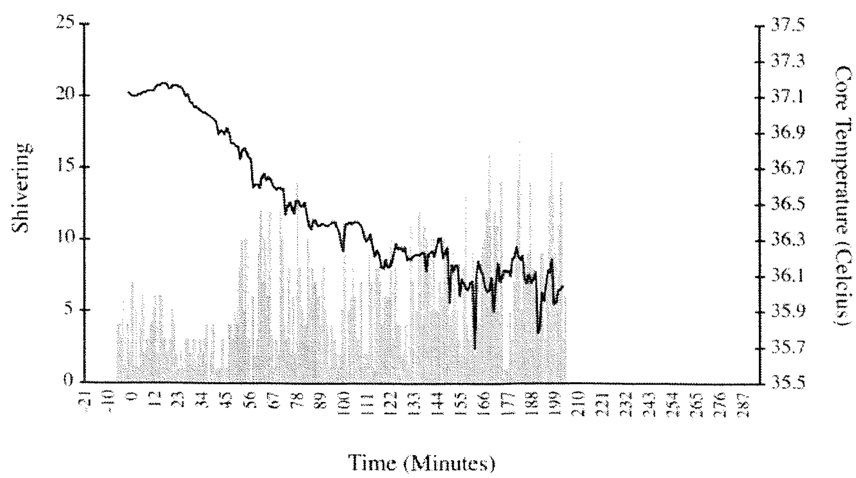

Fig. 5. Data collected from a volunteer during a study conducted in a climatic chamber. The study evaluated the effects of cold air (10° C) on physiological and psychological function. Core temperature (the continuous black line) is presented in degrees C. Shivering (the gray bars), defined as movement with a frequency of approximately 10 Hz, is presented in arbitrary units. The cold exposure began at time 0 identified on the x-axis in minutes and ended after approximately 200 minutes had elapsed.

The second generation device, like the first generation device, can assess high frequency activity when used in a special High Frequency (HF) mode. When in that mode, it retains the capability of assessing other frequency domains, as well the standard actigraphic channels used for sleep analysis. However, due to limitations in microprocessor speed and program memory (as opposed to data memory), the second generation device can not also simultaneously collect behavioral data or data from any of the environmental channels in the HF mode and can only collect data in this mode for 2.4 days. The HF mode stores activity data so that a Fast Fourier algorithm can be used to classify motion into various frequency domains, ranging from 0 to 25 Hz (Fig. 6). This analysis is conducted off-line once the data are downloaded to a personal computer. Since the third generation device has a more powerful microprocessor and more program memory than the second generation device, it can acquire data in the HF mode, perform an on-line Fast Fourier analysis, simultaneously store information in the standard actigraph channels and record any desired combination of environmental and behavioral information. The capability of performing an on-line frequency analysis will give the device the ability to provide the user feedback in real time as to his/her activity profile in any frequency domain and therefore potentially modifying this activity. Also, running the Fast Fourier algorithm in real time will greatly increase the run time of the device.

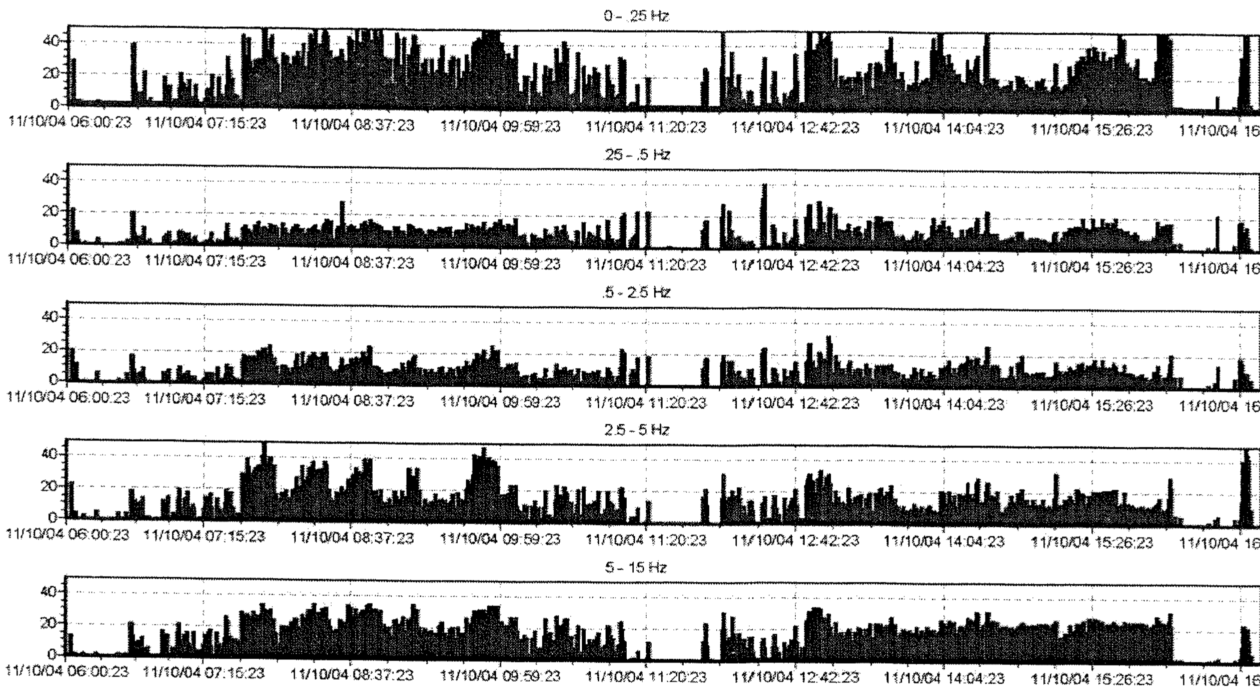

Fig. 6. Data collected using the High Frequency (HF) mode with the 2nd generation Vigilance monitor.

5. RESEARCH APPLICATIONS

One of the most successful studies that employed the vigilance monitor assessed the effects of a nutritional intervention on soldiers engaged in a training exercise. The exercise was conducted solely for the purpose of testing the efficacy of providing supplemental energy in the form of a carbohydrate beverage, so it was possible to conduct a well-controlled study. This field exercise was designed, in collaboration with the military unit, the 75th Ranger Regiment, to simulate a brief, but intense, light infantry mission, so the test would be realistic in terms of the unit's operational requirements. In that study the vigilance monitor was the primary dependent measure used to assess soldier cognitive performance and it successfully documented the beneficial effects of the carbohydrate beverage on vigilance compared to a placebo beverage.[11]

The functionality of the monitors has also been evaluated in different training environments. The data shown in Fig. 7 were collected from a volunteer engaged in an intense 8-day field exercise, a standard part of the U.S. Marine Infantry Officer Training course in Quantico, VA., which was conducted in a hot, humid environment. Patterns of rest and activity, and environmental conditions were documented by the monitor (Fig. 7). Vigilance data were also acquired, although only for brief periods of time. Data from another field study conducted at the Yakima Training Center, WA. with a mechanized infantry unit (Stryker) are presented in Fig. 8. This exercise included movement in Stryker vehicles, and various tasks associated with mechanized infantry training. During the study, the soldiers generally slept in their vehicles. Sleep time, as estimated by a standard algorithm,[9] is shown on the bottom axis of Fig. 8 and these data indicate the volunteer slept reasonably well in the vehicle.

Currently the second and third generation devices are in use in a series of studies. One is examining the ability of mulifrequency actigraphy to improve estimates of energy expenditure compared to the standard actigraph. Another study is using the devices to assess shivering. Several studies are planned in which the monitor will assess vigilance as volunteers navigate through complex environments. In one laboratory study, the monitors are being used to examine the effects of different diets on cognitive performance and activity patterns. The versatility of these devices, given their computational power, memory capacity, environmental monitoring and advanced actigraphic functions, in combination with their behavioral assessment capabilities, has only begun to be explored. We believe they are particularly well suited for examining, and if desired modifying, cognitive performance as humans go about their daily lives, particularly in the environments in which warfighters must operate. This was what they were designed to accomplish.

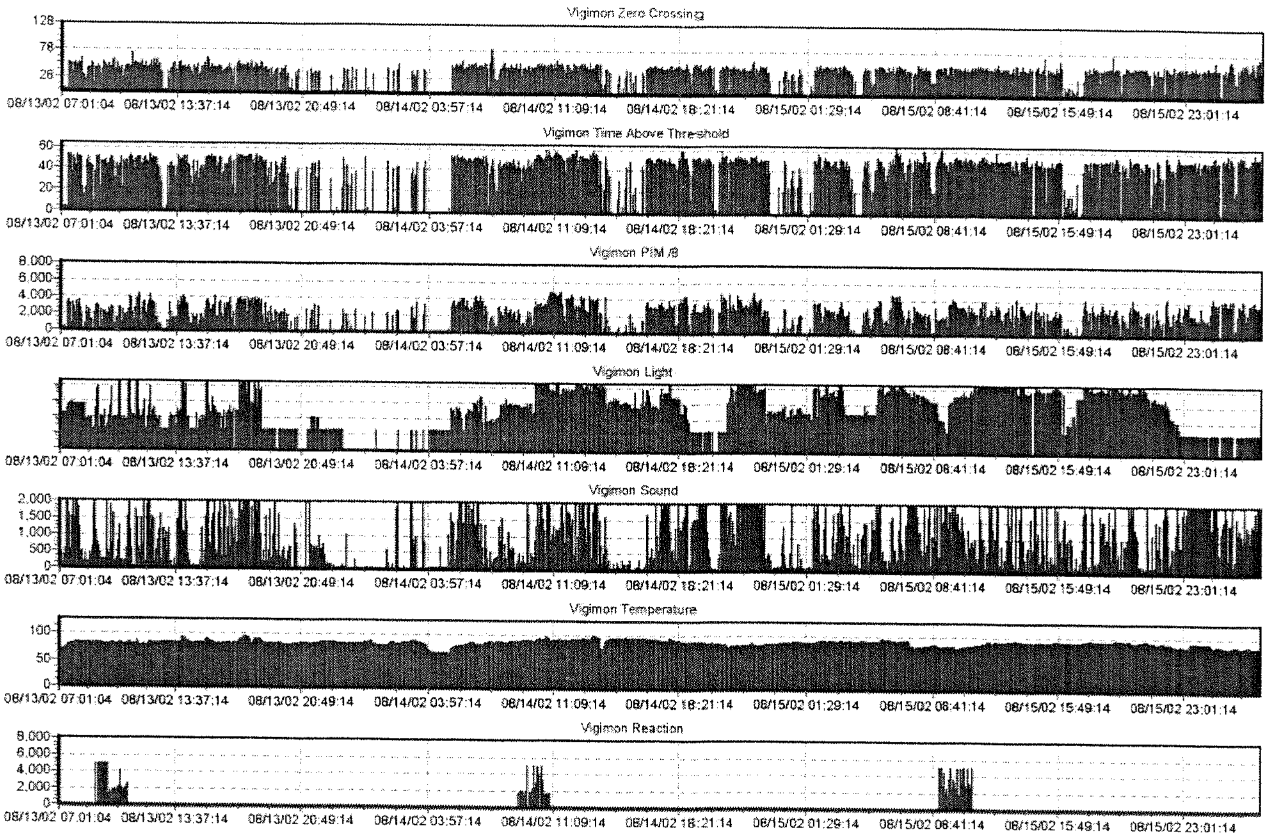

Fig 7. Vigilance monitor data collected during part of an 8–day U.S. Marine Infantry Officer Training exercise. On Aug. 14 the unit engaged in simulated night attack; on Aug. 15 another night attack scenario was the activity.

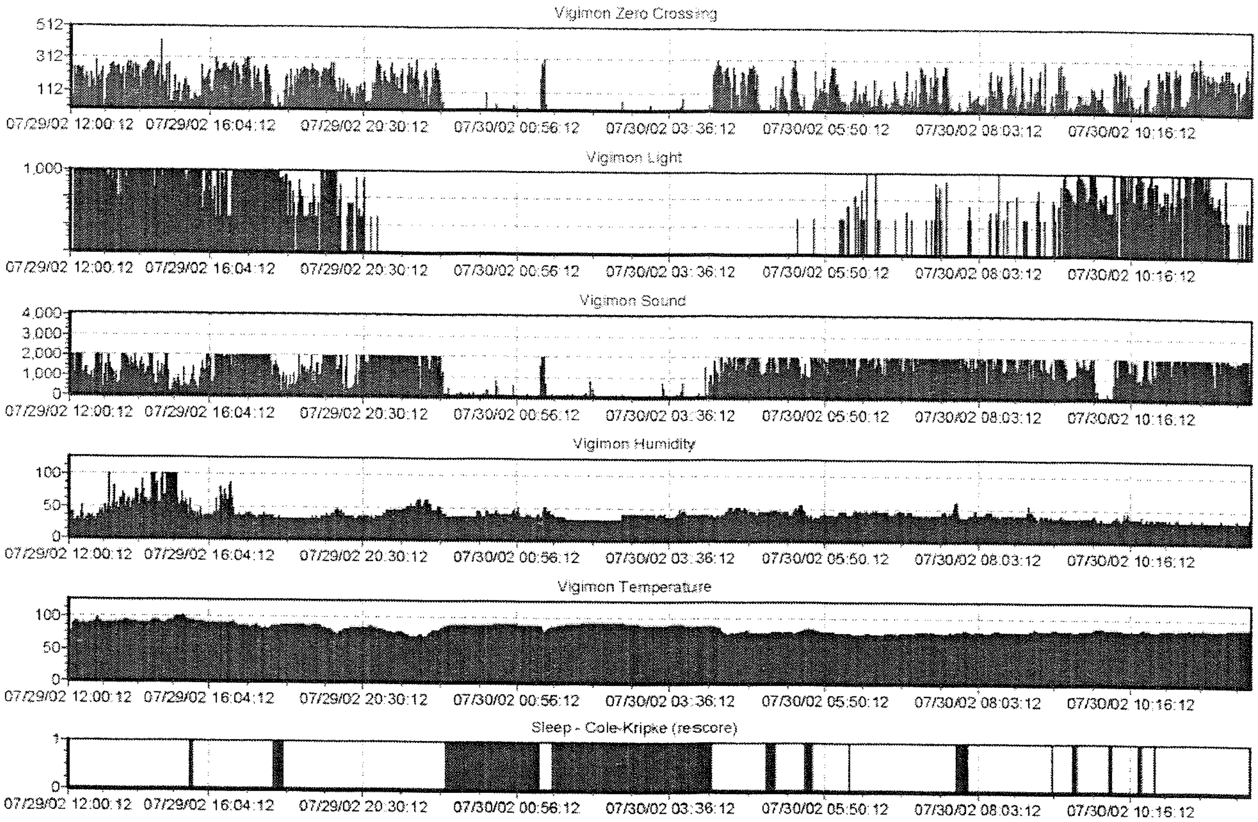

Fig. 8. Data from a field study conducted at the Yakima Training Facility in Washington State with a mechanized infantry unit (Stryker). Sleep as estimated by a standard algorithm (Cole-Kripke) is shown on the bottom axis of the figure.

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This paper is dedicated to the memory of Mr. Mark Godwin, without his key contributions the 2nd and 3rd generation vigilance monitors could not have been designed or produced. Approved for public release: distribution is unlimited. The opinions or assertions contained herein are the private views of the author(s) and are not to be construed as official or reflecting the views of the Army or the Department of Defense. The investigators have adhered to the policies for protection of human subjects as prescribed in Army Regulation 70-25, and the research was conducted in adherence with the provisions of 45 CFR Part 46. Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRMC Regulation 70-25 on the use of volunteers in research. Any citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement of approval of the products or services of these organizations.

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